Section 22 Rhode Island

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Guidance for Estimating Probable Yields of Surface Water Systems in Rhode Island

December 1989

US Army Corps of Engineers
New England Division

GUIDANCE FOR ESTIMATING PROBABLE YIELDS OF SURFACE WATER SYSTEMS IN RHODE ISLAND

prepared for
The State of Rhode Island

DEPARTMENT OF THE ARMY
NEW ENGLAND DIVISION, CORPS OF ENGINEERS
WALTHAM, MASSACHUSETTS

December 1989

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GUIDANCE FOR ESTIMATING PROBABLE YIELDS OF SURFACE WATER SYSTEMS IN RHODE ISLAND

1. PURPOSE

This report presents a review and analysis of storage-yield relationships considered generally applicable for watersheds in the State of Rhode Island. These relationships were derived via statistical transformation of data obtained from U.S. Geological Survey (USGS) records and through development of mass curves for the critical drought of the 1960's. A rainfall frequency analysis was also performed. Included are sections describing the surface water hydrology of small watersheds in Rhode Island, analysis of data, and the development of storage yield relations. The study was performed at the request of the State of Rhode Island, Department of Planning.

2. AUTHORITY

Authority for the study and report is contained in Section 22 of the Water Resources Development Act (PL 93-251) of 1974. Section 22 reads in part as follows: ". . . The Secretary of the Army, acting through the Chief of Engineers, is authorized to cooperate with any State in the preparation of comprehensive plans for the development, utilization and conservation of the water and related resources. . ."

3. UNITS AND CONVERSIONS

The gallon is the unit of volume most used by domestic water suppliers, whereas, the cubic foot is more common to the watershed hydrologist. Some units frequently used and their conversions are listed in table 1 as an aid to common understanding.

4. DEFINITION OF TERMS

a. Dependable Yield. Dependable, safe, or firm yield is the maximum water supply that can be provided continuously from a source during a critical period. The dependable yield of a surface water source will vary with the severity of the critical drought test period selected. There is no way of reliably predicting the severest possible drought, and if there were, it probably would not be practical to design for such a condition but rather accept some degree of risk. In

TABLE 1

UNITS AND CONVERSIONS

Area

1 Acre = 43,560 Square Feet (Ft^2)

1 Square Mile = 640 Acres

Volume

1 Cubic Foot (Ft^3) = 7.48 U.S. Gallons (Gal.)

1 U.S. Gallon = 0.1337 Cubic Foot (Ft^3)

1 Acre-Foot (Ac-Ft) = 43,560 Cubic Feet (Ft^3)

1 Acre-Foot (Ac-Ft) = 0.3258 Million Gallon (MG)

1 Million Gallons (MG) = 3.0689 Acre-Feet (Ac-Ft)

Flow

1 Cubic Foot Per Second (CFS) = 448.33 U.S. Gallons Per Minute (GPM)

1 Cubic Foot Per Second (CFS) = 0.6464 Million Gallon Per Day (GPD)

1 Cubic Foot Per Second (CFS) = 2.0 Acre-Feet Per Day (Ac-Ft/Day)

1 Gallon Per Minute (GPM) = .0022 Cubic Foot Per Second (CFS)

1 Million Gallons Per Day (MGD) = 1.547 Cubic Feet Per Second (CFS)

1 Million Gallons Per Day (MGD) = 3.094 Acre-Feet Per Day (Ac-Ft/Day)

practice, the critical period is often taken as the period of lowest known natural historical flow in the region. This was the criteria used in this study for determining dependable yield. Another criteria sometimes used is the drought of a selected, statistically determined, frequency, i.e., a 1 percent annual chance event with complete utilization of storage or a 5 percent chance event with 75 percent utilization of storage, with the idea that measures could be implemented to curtail water use during the rarer events. The record drought in Rhode Island, used as the test criteria in this study, is considered to have an annual chance of occurrence in the range of 1 to 2 percent (100 to 50-year) as discussed later in this report.

The current study dealt with determining dependable yield of surface water systems operating as independent water supply sources. The combined dependable yield of integrated systems, made up of multiple reservoirs and other sources, is sometimes greater than the sum of the yields of the individual parts. For example, a river source may have a low dependable yield because of seasonally low river flow and a large reservoir may have a low yield because of inadequate catchment area for timely reservoir refill but the dependable yield of the two, as an integrated system, can be significantly greater than the sum of the two individual dependable yields. Establishing the dependable yields of comprehensive integrated water supply systems in Rhode Island was beyond the scope of this study.

b. Drought. A drought is a prolonged period of below normal precipitation which seriously affects normal streamflows and ground water levels.

c. Reservoir Storage. Reservoir storage is the usable volume of water that can be impounded. It is that capacity that can be filled and emptied as needed for water supply purposes.

d. Watershed. Watershed is the rainfall catchment area draining to a stream, river, or reservoir.

5. RHODE ISLAND SURFACE WATER HYDROLOGY

a. Climatology. The State generally receives ample amounts of precipitation throughout the year. Rhode Island's variable climate is characterized by frequent but generally short periods of heavy precipitation. The moderating effect of the Atlantic Ocean gives coastal Rhode Island a relatively mild winter and less precipitation in the form of snow. The coast also escapes the extreme heat in summer experienced by interior areas of southern New England.

b. Temperature. Average monthly temperatures vary widely throughout the year. Extremes in temperature may range from occasional highs above 100 °F, to infrequent lows below minus 10 °F. The average annual temperature at Providence and Newport is 50.5 °F (see table 2).

c. Precipitation. Cyclonic cooling of air may occur via adiabatic expansion of rising air, or from the meeting of the two very different air masses (i.e., warm, moist air converging with a cold air mass), or through contact between moist air and cold ground. As moist (water vapor-laden) air is cooled to near its dewpoint, cloud droplets are formed. The growth of these cloud droplets to precipitable rain or snow is governed by a variety of meteorological conditions.

The State of Rhode Island lies in the path of "prevailing westerlies" and other cyclonic storms that move easterly across the country from the western and southwestern United States. Being a coastal State, Rhode Island is also subjected to coastal storms which travel up the Atlantic seaboard from off the Carolinas. Thunderstorms can occur over the basin at any time of the year and may be of local origin or associated with a frontal system. The mean annual precipitation rain, snow, sleet, etc.) for Rhode Island is approximately 45 inches. Summaries of precipitation amounts at Providence and Woonsocket, Rhode Island are presented in tables 3 and 4.

d. Snowfall. The annual average snowfall in Rhode Island varies from about 30 inches near the coast to 50 inches in the upland areas in the northwest corner of the State. Monthly snowfall recorded at Woonsocket (1956-1986) and Providence (1949-1986) is presented in table 5.

e. Topography. The topography in Rhode Island has been modified by glacial forces. The Coastal Lowland encompasses the southern and eastern regions of the State with small lakes, broad swamps and wide valleys with a few low, rounded hills. Increasing relief and forested land comprise the central region where low to moderate sized hills, lakes and ponds of a variety of sizes are found. The eastern New England upland covers the northwestern one-third of Rhode Island with wooded, rolling hills, rising above lakes and swamps in the narrow valleys. This region is rough and hilly and has a much higher elevation than the coastal lowlands. The land rises from about 200 feet above sea level in the east to more than 800 feet in the northwest. Land regions in Rhode Island are depicted in plate 1.

f. Runoff/Streamflow. The USGS maintains several streamflow gages in Rhode Island. For this report data from

TABLE 2

SUMMARY OF TEMPERATURES
DEGREES FAHRENHEIT

	Providence, Rhode Island (81 Years of Record)			Newport, Rhode Island (30 Years of Record)		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum
January	28.9	36.7	21.0	28.5	43	14
February	29.4	37.5	21.3	31.0	46	16
March	37.7	45.9	29.5	39.0	52	26
April	47.7	56.9	38.5	46.0	60	32
May	58.0	67.7	48.2	55.0	69	41
June	66.9	76.6	57.3	65.0	76	54
July	72.8	82.0	63.6	70.5	82	59
August	71.0	80.1	61.9	69.0	81	57
September	63.8	73.2	54.5	65.0	78	52
October	53.8	63.2	44.4	55.0	67	43
November	43.4	51.4	35.4	45.0	58	32
December	32.6	40.2	25.0	35.0	50	20
ANNUAL	50.5	59.3	41.7	50.5	60	41

TABLE 3

PRECIPITATION DATA FOR PROVIDENCE, RI
1832-1986
UNITS IN INCHES

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JULY	AUG.	SEP.	OCT.	NOV.	DEC.	TOTAL
1832	3.87	4.25	3.20	3.33	4.14	.33	1.82	3.92	3.50	2.01	3.46	5.63	39.46
1833	1.71	1.55	1.97	3.17	.99	4.81	1.11	2.15	1.53	5.98	4.50	4.67	34.14
1834	1.57	1.13	1.43	3.13	5.61	5.10	7.58	1.15	3.81	4.64	3.80	2.97	41.92
1835	3.50	1.20	4.60	4.06	1.50	1.95	2.84	2.25	.83	3.26	1.72	3.25	30.96
1836	5.63	3.45	5.00	2.30	2.51	3.25	1.53	.72	1.03	2.35	5.25	4.85	37.87
1837	1.40	2.65	3.17	4.65	7.28	2.82	1.38	2.00	.48	1.29	1.95	2.55	31.62
1838	2.70	2.32	2.70	2.70	3.88	3.30	.63	3.55	6.76	4.61	3.65	1.08	37.88
1839	.76	1.50	1.50	3.63	3.79	2.31	5.26	5.00	1.83	3.75	2.30	5.12	36.75
1840	2.80	2.05	3.50	3.45	3.35	2.89	3.38	3.20	2.95	5.17	5.35	3.10	41.19
1841	6.45	1.50	2.86	7.78	2.18	.98	5.13	5.12	2.35	3.20	4.45	5.86	47.86
1842	1.30	4.05	2.07	2.10	3.40	9.65	1.48	3.35	1.40	1.16	3.82	3.93	37.71
1843	.60	5.27	5.58	4.34	3.50	2.12	1.83	6.23	2.20	6.45	1.35	3.03	42.50
1844	4.32	1.95	4.75	.67	1.95	1.15	4.42	1.11	2.83	5.80	3.30	2.75	35.00
1845	3.20	2.70	3.53	2.34	2.75	2.32	3.10	5.63	1.63	3.40	9.08	3.48	43.16
1846	1.82	2.08	2.86	1.75	4.58	1.30	1.44	2.73	2.33	1.85	4.62	3.15	30.51
1847	2.13	2.71	3.17	1.72	2.02	6.98	2.28	5.50	8.35	1.95	5.72	5.97	48.50
1848	4.82	3.80	2.40	.95	5.00	3.80	1.85	3.73	2.45	4.05	3.80	3.83	40.48
1849	.80	.60	5.99	1.62	3.43	1.23	2.00	3.39	3.14	6.55	2.42	3.52	34.69
1850	5.60	3.38	5.19	4.67	5.00	2.60	2.35	7.65	5.00	2.10	2.10	5.85	51.49
1851	1.93	3.87	2.00	7.80	3.58	1.90	5.19	3.77	2.47	3.20	5.05	2.62	43.38
1852	2.70	2.00	3.55	6.65	2.00	1.00	1.68	8.00	1.40	1.30	4.60	3.70	38.58
1853	4.27	5.75	1.35	5.05	4.95	.90	6.37	8.38	3.80	4.15	4.40	3.90	53.27
1854	1.80	4.85	2.85	6.30	3.60	3.60	2.45	.30	6.10	1.90	9.15	3.35	46.25
1855	6.45	4.05	.85	2.50	2.55	1.95	3.25	2.02	.25	5.33	3.75	6.10	39.05
1856	5.25	.80	1.55	2.80	4.10	2.47	4.20	5.75	5.10	1.15	2.00	5.80	40.97
1857	5.50	2.36	3.35	6.29	4.33	1.90	3.45	4.80	2.27	2.90	2.40	5.20	44.75
1858	3.33	2.80	2.05	3.63	2.35	5.55	4.90	8.20	3.05	2.80	2.40	3.45	44.51
1859	5.75	1.85	8.00	2.28	3.40	7.06	1.14	3.69	3.65	2.62	2.27	3.45	45.16
1860	1.00	3.54	1.80	1.55	1.65	4.02	3.09	5.70	5.38	2.10	3.95	4.66	38.44
1861	4.87	2.95	4.62	7.75	3.22	4.61	2.21	4.50	2.75	2.17	3.20	1.40	44.25
1862	6.06	3.15	4.12	1.60	2.60	6.75	3.52	1.47	7.35	4.77	6.85	2.10	50.34
1863	4.61	4.04	4.88	5.52	2.33	1.90	9.42	4.59	1.74	2.97	7.51	5.66	55.17
1864	4.66	1.53	4.74	2.46	3.15	1.22	1.46	4.05	2.36	2.85	3.42	4.95	36.85
1865	5.29	5.45	5.56	2.98	6.23	1.56	3.91	.74	.27	4.60	4.03	4.08	44.70
1866	2.35	5.64	4.29	2.02	5.29	4.43	2.03	3.54	5.75	2.78	3.97	3.96	46.05
1867	5.72	6.80	5.32	2.24	3.94	1.56	3.15	8.23	.62	4.07	2.59	2.80	47.04
1868	4.56	1.71	4.63	7.02	10.57	4.42	2.09	4.55	5.95	1.23	4.39	2.40	53.52
1869	3.92	5.19	6.34	2.07	5.20	5.63	.88	1.58	5.08	5.92	2.19	4.70	48.70
1870	6.22	3.34	5.47	5.50	2.55	8.22	2.48	1.71	2.11	5.62	2.83	2.97	49.02
1871	2.35	3.80	5.25	3.81	3.80	5.57	3.63	5.73	1.00	6.68	3.35	2.94	47.91
1872	2.45	1.56	5.02	2.35	3.64	3.03	5.31	6.12	6.18	5.34	4.95	2.76	48.71
1873	5.56	4.60	3.67	3.57	4.62	2.74	2.89	7.89	2.17	4.80	5.16	4.99	52:66
1874	3.62	4.40	2.00	8.54	3.04	3.21	2.58	7.71	2.20	.92	2.66	2.51	43.39
1875	3.54	3.76	4.57	5.02	3.44	7.27	3.56	8.85	2.05	4.07	5.12	.97	52.22
1876	1.28	4.42	9.75	4.24	3.23	1.40	4.14	1.82	5.73	2.15	6.95	5.25	50.36
1877	4.55	.33	7.99	2.40	4.40	4.60	3.60	6.41	.90	5.81	6.41	1.40	48.80
1878	3.53	5.70	3.86	5.42	2.00	4.59	2.31	3.88	1.25	4.57	8.81	6.56	52.48
1879	2.91	4.32	5.59	4.67	1.27	3.10	4.10	5.03	2.42	1.00	2.53	3.65	40.59
1880	2.88	5.53	4.59	3.25	.83	1.05	6.07	5.19	2.09	3.06	3.14	3.61	41.29
1881	6.17	6.30	5.30	1.56	2.26	6.10	4.09	.49	2.02	2.46	4.65	3.39	44.79
1882	7.99	4.90	3.50	2.81	3.83	2.32	1.93	1.53	7.83	2.78	2.29	3.25	44.96

TABLE 3 (continued)

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JULY	AUG.	SEP.	OCT.	NOV.	DEC.	TOTAL
1883	5.97	4.50	2.58	2.04	4.33	1.26	3.18	.83	2.50	5.23	2.59	4.53	39.54
1884	4.96	6.46	4.58	4.35	3.20	3.87	3.07	4.03	1.23	2.74	3.55	6.72	48.76
1885	6.03	4.13	1.50	2.85	3.53	2.07	2.20	4.78	.80	5.51	3.50	2.71	39.61
1886	7.10	11.31	3.28	2.87	3.86	1.31	1.99	4.22	2.77	3.53	3.86	5.92	52.02
1887	6.61	5.87	4.74	4.40	2.23	4.24	6.09	5.87	1.58	2.99	2.16	4.20	50.98
1888	4.63	4.29	6.65	2.81	5.65	1.07	2.55	7.84	9.19	5.37	9.02	4.37	63.44
1889	5.62	2.55	1.98	4.07	4.71	2.90	9.49	5.83	5.23	4.52	6.39	2.62	55.91
1890	2.79	3.35	8.27	3.59	5.47	2.68	1.81	2.61	4.82	9.19	.74	5.28	50.60
1891	8.14	6.00	5.55	3.58	2.29	3.50	3.31	6.26	2.77	4.70	2.84	4.25	53.19
1892	5.15	1.72	4.45	1.39	6.07	2.89	1.86	3.07	1.81	1.36	6.12	1.50	37.39
1893	3.47	7.88	5.59	4.51	6.24	3.59	1.10	4.24	2.27	4.25	2.72	5.42	51.28
1894	4.14	4.55	1.33	3.72	5.04	.56	.77	2.14	3.09	6.79	3.52	5.62	41.27
1895	5.74	1.90	3.31	6.25	3.88	2.66	4.64	2.71	2.20	8.08	6.66	2.78	50.81
1896	3.52	6.62	6.14	1.22	3.13	3.90	1.34	2.56	8.53	2.71	3.37	2.87	45.91
1897	6.24	3.00	2.95	3.30	4.46	3.31	5.56	4.47	1.77	.49	7.09	4.99	47.63
1898	6.01	6.45	2.95	6.08	4.07	1.16	10.26	6.00	2.26	8.43	7.29	2.54	63.50
1899	5.18	6.00	8.38	2.12	2.60	3.62	4.69	1.56	9.16	1.68	2.37	1.88	49.24
1900	4.20	8.17	5.67	1.90	6.24	2.19	2.04	3.13	4.05	2.86	4.54	2.79	47.78
1901	1.93	1.00	8.10	8.90	6.85	1.00	2.93	2.56	4.17	2.98	2.24	9.40	52.06
1902	2.06	6.97	5.71	3.09	1.20	4.17	3.41	2.39	6.55	4.57	1.80	6.40	48.32
1903	4.98	5.64	8.17	4.01	.58	6.64	4.75	3.92	1.00	2.89	1.77	3.56	47.91
1904	6.45	3.38	3.92	9.45	2.37	2.46	1.06	5.12	5.34	2.11	1.95	4.31	47.92
1905	2.45	1.18	1.98	3.09	1.62	5.63	2.64	3.00	5.70	1.88	1.57	3.92	34.66
1906	2.59	2.88	4.29	2.07	4.51	3.40	5.29	2.51	3.18	4.91	1.90	3.81	41.34
1907	2.63	2.36	1.78	4.24	3.72	2.22	1.06	.88	8.66	3.44	4.60	4.96	40.55
1908	2.93	4.00	3.42	1.77	4.18	2.01	4.33	5.16	.88	3.37	.92	3.12	36.09
1909	3.06	5.80	2.86	5.07	2.09	1.61	.58	2.50	3.28	1.25	2.95	2.70	33.75
1910	4.85	3.86	1.32	1.64	2.90	3.98	2.86	2.62	2.68	1.60	3.37	2.53	34.21
1911	2.71	2.38	3.16	3.14	2.04	1.86	3.23	4.86	2.01	2.79	5.61	3.01	36.80
1912	4.09	2.65	6.36	3.61	3.99	.63	1.76	2.90	1.87	2.37	2.81	5.61	38.65
1913	2.90	2.97	4.30	5.32	1.84	1.19	2.29	2.36	2.90	5.45	1.96	3.46	36.94
1914	3.56	2.99	3.38	3.94	1.88	.58	2.81	2.02	.48	2.97	1.96	2.93	29.50
1915	6.86	3.30	.07	1.58	1.82	1.29	6.35	4.48	.88	1.86	1.67	3.80	33.96
1916	1.35	4.34	2.46	2.89	3.85	4.20	6.37	.78	.86	2.39	1.92	3.03	34.44
1917	3.01	1.97	4.14	2.62	3.39	4.33	1.09	5.90	2.28	5.02	.31	2.10	36.16
1918	3.11	2.87	1.77	3.74	2.07	3.12	4.44	2.41	8.04	.65	2.01	3.14	37.37
1919	4.34	3.09	4.31	3.32	3.79	3.32	3.68	5.14	5.80	1.49	3.79	2.11	44.18
1920	2.60	4.56	3.66	4.70	4.92	6.80	3.00	3.17	2.11	1.44	3.69	3.91	44.56
1921	3.32	2.23	2.50	4.21	2.60	3.35	5.35	1.88	1.33	1.23	6.35	2.43	36.78
1922	1.36	2.42	4.67	2.18	4.24	6.56	6.88	6.96	3.28	2.66	1.09	2.58	44.88
1923	6.55	1.97	3.14	4.75	1.19	4.31	3.09	1.48	1.52	4.09	3.62	5.13	40.84
1924	4.13	3.67	1.34	3.77	2.71	1.05	1.12	5.39	6.71	.15	1.48	1.96	33.48
1925	3.21	2.08	3.79	1.95	1.92	1.73	3.56	1.88	2.58	3.53	4.11	3.28	33.62
1926	2.69	3.82	3.14	2.12	2.48	1.52	2.88	4.20	1.58	4.62	5.30	2.75	37.10
1927	2.69	2.02	1.47	1.88	2.76	3.04	4.16	10.88	2.48	4.18	3.11	4.69	43.36
1928	2.27	2.85	2.64	3.69	1.18	3.70	5.00	4.03	3.25	3.63	2.13	2.87	37.24
1929	4.49	3.04	3.17	5.94	3.45	.96	1.41	2.44	2.27	2.70	2.47	3.84	36.18
1930	2.62	2.57	3.02	1.08	2.21	2.71	3.80	2.14	1.23	3.60	3.32	2.67	30.97
1931	3.42	1.98	4.14	2.68	4.07	4.95	3.03	4.99	1.37	2.40	.83	3.20	37.06
1932	4.45	1.76	4.69	1.98	2.51	2.44	2.83	4.86	8.48	4.49	4.49	1.66	44.64

TABLE 3 (continued)

YEAR	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JULY	AUG.	SEP.	OCT.	NOV.	DEC.	TOTAL
1933	2.02	3.15	5.70	5.33	4.10	2.85	2.24	2.68	6.20	2.59	1.35	2.96	41.17
1934	3.80	3.38	3.82	4.00	3.50	3.33	.82	2.34	4.13	2.26	3.88	3.10	38.36
1935	6.02	2.64	1.60	3.37	1.51	4.53	2.72	1.14	2.95	.76	4.29	1.05	32.58
1936	6.84	3.77	6.78	3.79	1.68	2.92	2.34	3.00	5.29	2.49	1.05	9.44	49.39
1937	4.61	1.75	3.82	5.27	2.54	3.14	1.16	4.13	3.01	4.06	5.42	3.22	42.13
1938	4.37	2.34	2.39	2.22	4.49	7.21	6.92	2.21	5.16	3.01	3.40	3.31	47.03
1939	2.30	4.09	4.62	4.33	.57	2.70	1.07	4.08	2.39	4.31	.76	3.12	34.34
1940	2.50	3.13	3.69	5.30	5.01	2.22	3.24	.99	2.57	1.86	6.38	2.15	39.04
1941	3.57	2.34	3.54	1.53	3.10	4.01	5.68	2.45	1.03	1.07	2.79	3.37	34.48
1942	3.98	3.84	7.98	.72	1.77	3.44	4.56	4.54	1.68	3.09	5.03	6.39	47.02
1943	4.07	1.61	3.74	3.72	3.34	1.88	1.97	.82	1.24	4.39	2.32	1.15	30.25
1944	2.58	2.52	5.00	3.82	.86	4.16	.96	1.34	9.74	3.33	7.52	3.42	45.25
1945	4.08	4.26	2.21	2.57	4.25	3.97	1.98	2.63	1.87	2.29	8.50	7.82	46.43
1946	3.63	3.55	1.49	2.25	3.99	2.91	1.25	12.24	1.70	.16	.67	3.84	37.68
1947	2.85	1.83	3.36	4.91	3.73	3.93	4.71	2.01	2.96	2.27	5.42	3.73	41.71
1948	6.15	2.34	3.73	3.71	9.25	2.73	4.93	2.88	2.36	4.85	5.00	2.30	50.23
1949	4.35	3.48	1.97	4.85	2.72	.05	1.56	4.73	4.85	2.11	2.96	2.02	35.65
1950	3.51	3.83	3.79	2.92	2.51	2.02	1.42	3.60	2.09	2.71	6.89	4.22	39.51
1951	4.50	3.39	5.29	3.57	4.50	2.64	.91	2.36	1.74	3.27	8.26	5.17	45.60
1952	4.59	4.37	4.72	4.30	4.22	2.11	.32	7.45	2.64	1.62	1.78	3.42	41.54
1953	7.12	4.51	4.73	6.70	3.25	.55	4.43	3.99	2.99	4.71	6.59	5.42	54.99
1954	2.84	2.68	3.53	4.91	5.92	1.31	2.56	8.30	6.04	2.79	4.92	5.73	51.53
1955	.78	4.97	5.35	3.61	2.37	3.72	3.34	11.12	3.27	7.00	5.60	.58	51.71
1956	4.92	4.60	5.51	3.08	1.43	1.57	4.92	.91	3.10	3.74	3.62	5.27	42.67
1957	2.17	1.68	3.29	4.46	.93	.39	1.41	2.51	.87	2.52	3.99	5.86	30.08
1958	7.12	2.95	3.45	7.21	4.05	3.15	6.29	5.15	5.02	3.08	2.58	1.49	51.54
1959	2.27	3.67	6.04	3.83	1.46	4.83	4.01	3.53	.77	4.71	3.85	4.17	43.14
1960	3.02	5.63	2.48	2.94	3.79	1.26	4.61	1.06	5.98	2.24	2.77	4.30	40.08
1961	3.52	4.68	4.16	7.32	5.21	1.48	2.76	3.86	7.92	2.39	3.10	3.16	49.56
1962	4.70	5.16	1.93	3.85	2.14	5.52	1.62	2.73	3.67	11.89	4.49	2.63	50.33
1963	3.40	3.15	3.78	1.62	4.69	3.54	3.35	1.56	4.10	1.63	6.53	2.15	39.50
1964	5.65	3.15	2.26	5.34	.71	2.34	2.63	2.38	3.95	2.11	2.43	5.46	38.41
1965	3.46	3.77	1.72	2.43	1.08	1.91	1.28	1.90	1.64	2.75	2.08	1.42	25.44
1966	3.40	4.30	2.40	1.48	3.85	2.31	2.77	3.37	5.23	2.60	3.93	3.04	38.68
1967	1.60	2.51	5.49	4.19	7.27	2.72	3.95	3.24	3.17	2.25	2.75	7.36	46.50
1968	3.50	1.31	7.83	1.49	3.54	4.74	1.49	1.61	1.14	1.79	6.22	6.70	41.36
1969	2.23	4.30	3.10	3.95	2.41	1.23	2.98	2.58	3.09	1.62	6.35	10.75	44.59
1970	.50	5.34	4.75	3.91	3.03	4.25	1.00	6.59	1.79	4.41	5.31	4.54	45.42
1971	2.01	5.36	3.81	2.31	3.83	1.64	3.48	3.03	2.54	2.88	5.16	2.37	38.42
1972	1.85	5.19	6.70	3.71	5.73	6.83	4.25	2.98	7.31	4.36	8.45	7.70	65.06
1973	3.06	3.55	2.78	7.16	3.99	3.48	2.92	5.17	3.04	3.17	2.29	7.63	48.24
1974	4.45	3.04	4.51	2.86	2.74	3.28	1.64	3.10	6.15	2.79	1.56	4.54	40.66
1975	6.78	3.29	3.07	2.99	2.06	4.73	3.51	2.19	6.15	4.66	6.29	5.11	50.83
1976	6.38	2.91	3.44	2.00	2.53	1.60	8.08	7.01	1.57	6.52	.81	3.47	46.32
1977	3.90	2.87	5.62	3.35	3.43	3.92	2.04	2.12	5.60	6.90	3.24	5.85	48.84
1978	9.01	3.20	3.10	2.53	5.27	1.97	2.63	6.46	1.82	3.22	2.61	5.19	47.01
1979	11.66	4.08	2.21	5.12	7.62	1.44	1.65	10.09	4.08	3.94	4.49	1.81	58.19
1980	1.40	1.16	8.11	6.18	1.78	3.85	2.03	1.99	.90	3.41	3.73	1.57	36.11
1981	.77	4.79	.56	4.10	1.92	2.31	3.75	2.65	2.58	3.38	3.20	6.36	36.37
1982	6.09	3.08	3.76	3.64	1.61	11.08	3.51	3.67	3.61	3.08	4.32	1.81	49.26
1983	4.32	4.81	8.84	12.74	4.67	1.91	2.14	2.71	2.16	4.50	11.01	7.71	67.52
1984	2.00	7.20	5.77	4.30	8.38	4.09	5.16	.71	1.77	4.25	1.95	3.16	48.74
1985	1.18	1.57	3.08	1.65	4.76	4.70	2.88	8.57	1.69	1.78	7.14	1.42	40.42
1986	5.88	3.18	2.86	2.10	2.29	3.27	5.95	3.29	.97	2.48	5.29	7.74	45.30

THE AVERAGE ANNUAL PRECIP. IS 43.41 INCHES

TABLE 4

PRECIPITATION SUMMARY (INCHES)
WOONSOCKET, RHODE ISLAND
(35 Years of Record - 4/48 to 11/86)

Month	Mean	Maximum	Minimum
January	4.02	11.99	0.76
February	4.01	9.84	1.03
March	4.24	9.77	0.81
April	3.99	10.37	0.69
May	3.45	8.50	0.53
June	3.40	12.12	0.20
July	3.36	7.31	0.53
August	3.50	9.65	0.60
September	3.72	8.55	0.73
October	3.62	9.34	1.62
November	4.70	9.28	0.71
December	4.40	9.96	0.88
ANNUAL	45.03	64.82	27.35

Elevation 120 Feet

TABLE 5

SUMMARY OF SNOWFALL (INCHES)

	Providence, Rhode Island (38 Years of Record)			Woonsocket, Rhode Island (31 Years of Record)		
Month	Mean	Maximum	Minimum	Mean	Maximum	Minimum
January	9.36	28.70	0.50	11.43	33.60	0.00
February	10.21	30.90	0.00	13.08	52.10	0.00
March	7.34	31.60	0.00	9.26	38.50	0.00
April	0.72	7.60	0.00	0.84	6.00	0.00
May	0.19	7.00	0.00	0.00	0.00	0.00
June	0.00	0.00	0.00	0.00	0.00	0.00
July	0.00	0.00	0.00	0.00	0.00	0.00
August	0.00	0.00	0.00	0.00	0.00	0.00
September	0.00	0.00	0.00	0.00	0.00	0.00
October	0.13	2.50	0.00	0.07	2.00	0.00
November	0.73	4.40	0.00	0.87	4.80	0.00
December	6.45	19.80	0.00	9.38	23.10	0.00
ANNUAL	35.11	70.70	6.20	45.56	99.20	6.30

Elevation 50.00 Feet

Elevation 120.00 Feet

gaging stations at the following locations were analyzed:

(1) The Moshassuck River discharges into the Providence River, a tidal estuary which in turn empties into Narrangansett Bay. The lower Moshassuck receives effluent from the Central Falls wastewater treatment plant, textile wastes from Mills in Pawtucket and Saylesville, and is occasionally regulated at low flow by mills. The gaging station is located at Providence, one-half mile above the mouth, and has recorded runoff continuously since June 1963 from the 23.1-square mile drainage area.

(2) The Wood River, located in the Pawcatuck River basin, is formed by the confluence of Phillips and Acid Factory Brooks in the southwestern part of West Greenwich, Rhode Island. The Wood River flows in a general southerly direction about 17 miles to its junction with the Pawcatuck at the intersection of the town lines of Richmond, Hopkinton and Charlestown, RI, approximately 21.5 miles above the mouth of the Pawcatuck. Total fall of this tributary of the Pawcatuck is estimated at 110 feet. At Hope Valley, the Wood has experienced seasonal regulation by Locustville Pond on Brushy Brook since 1968. Also, there was some regulation at low flows by mills and ponds upstream until 1952; however, regulation was greater prior to 1948. There are two USGS gaging stations within this watershed at Hope Valley and Arcadia with drainage areas of 72.4 and 35.2 square miles, respectively. Discharge records for the Hope Valley gage include March 1941 to present. The Arcadia USGS gage records encompass January 1964 to September 1981, and October 1982 to present.

(3) The Nipmuc River, a minor tributary of the Blackstone, joins the Clear River just north of Harrisville, Rhode Island. The gaging station is located 1.2 miles northwest of Harrisville and has recorded streamflow from a 16-square mile drainage area since March 1964. Headwaters of the drainage area extend into Massachusetts south of Douglas, MA.

A map showing locations of the USGS gaging stations is provided on plate 3. Pertinent information on all USGS streamflow gages in Rhode Island is provided in table 6, and mean monthly flow data from the 4 gages used in this report is shown in table 7.

The mean annual runoff as measured by the gages utilized in this report ranges from 24.99 to 29.96 inches, averaging about 60 percent of the mean annual precipitation.

TABLE 6

USGS GAGING STATIONS
PERTINENT DATA

Name	Location	Drainage Area (sq.mi.)	Period of Record (years)	Average Flow CFS	Average Flow Inches
Wood River	Hope Valley	72.4	45	154.8	29.0
Wood River	Arcadia	35.2	21	77.2	29.8
Nipmuc River	Harrisville	16.0	22	30.2	25.6
Moshassuck River	Providence	23.1	23	40.8	24.0
Branch River	Forestdale	91.2	46	172.0	25.6
Blackstone River	Woonsocket	416.0	57	765.0	25.0
Woonasquatucket River	Centerdale	38.3	45	73.0	25.9
South Branch Pawtuxet River	Washington	63.8	46	130.0	27.7
Pawtuxet River	Cranston	200.0	46	343.0	23.3
Hunt River	East Greenwich	23.0	45	45.9	27.1
Chipuxet River	West Kingston	10.0	14	21.5	29.2
Usquepaug River	Usquepaug	36.1	12	78.9	29.7
Beaver River	Usquepaug	8.9	11	22.5	34.3
Pawcatuck River	Wood River Junction	100.0	46	195.0	26.5
Pawcatuck River	Westerly	295.0	45	578.0	26.6

TABLE 7

MEAN MONTHLY FLOWS (CFS)

Wood River at Hope Valley, RI
(45 Years of Record)

Month	Mean
October	74.20
November	127.00
December	178.00
January	198.00
February	220.00
March	281.00
April	258.00
May	191.00
June	135.00
July	72.50
August	62.30
September	60.60
Annual	154.80

Gage Elevation -
61.11 NGVD
Drainage Area - 72.4 sq.mi.

Wood River near Arcadia, RI
(21 Years of Record)

Month	Mean
October	35.00
November	64.00
December	95.70
January	103.00
February	111.00
March	141.00
April	132.00
May	92.70
June	64.30
July	34.90
August	29.70
September	22.90
Annual	77.20

Gage Elevation -
118.20 NGVD (Note
1982 Data Missing)
Drainage Area - 35.2 sq.mi.

Nipmuc River near Harrisville, RI
(22 Years of Record)

Month	Mean
October	10.70
November	24.30
December	38.50
January	43.50
February	44.80
March	65.50
April	56.70
May	35.20
June	25.30
July	7.67
August	5.91
September	4.48
Annual	30.20

Gage Elevation -
340.00 NGVD
Drainage Area - 16.0 sq.mi.

Moshassuck River at Providence, RI
(23 Years of Record)

Month	Mean
October	22.40
November	37.00
December	49.90
January	53.50
February	55.00
March	69.60
April	63.60
May	44.70
June	34.90
July	19.60
August	19.80
September	19.20
Annual	40.80

Gage Elevation -
8.19 NGVD (revised)
Drainage Area - 23.1 sq.mi.

g. Droughts. The drought of the 1960's in southeastern New England, for its duration, was the greatest experienced in the area in 200 years of record. The 1960's drought followed a period of above normal precipitation which contributed to relaxation on the part of cities and towns during what was really a period of rapidly increasing water demand.

The average annual precipitation recorded at Providence for climatic years 1963-1966, i.e., 1 April 1963 through 31 March 1967 was only 35.3 inches. The minimum annual precipitation during this period was 25.44 inches in 1965.

The accumulated deficiency in the average runoff of the Blackstone River at Woonsocket for water years 1964 through 1967, i.e., October 1963 through September 1967, was 27 inches, which is equivalent to more than one year's average runoff. Further the average flow of the South Branch Pawtuxet River was about 57 percent of normal for the period May 1964 to October 1966, equivalent to a runoff deficiency of more than 25 inches.

The frequencies of low precipitation for 1, 2, 3 and 4 consecutive calendar year durations were computed, and the 1, 3 and 4 year frequencies are shown graphically on plate 2. The annual curve was developed using 45 years of precipitation records at Providence, RI, in a Log Pearson Type III distribution. The frequencies for multiyear durations were determined using the partial duration series method discussed in Section 6, "Hydrologic Analyses." Based on this analysis the most critical 4-year period, climatic years 1963 through 1966, in the 1960's drought, with an average annual 4-year rainfall of 35.3 inches, has about a 1.8 percent chance of occurrence, equivalent to about a 55-year recurrence interval.

The above analysis was repeated using 155 years (1832 - 1986) of precipitation data (see plate 2A) and the 4-year drought period of the 1960's shifted to a 4 percent chance event or a 25-year return period; however, the annual frequency curve for 155 years of record was similar to the curve developed with 45 years of record. This additional analysis of extended precipitation data was performed to ascertain significant changes (if any) in nonexceedance probabilities from the shorter precipitation record of 45 years which coincided with the streamflow record of Wood River at Hope Valley.

6. HYDROLOGIC ANALYSIS

a. Hydrologic Data. Streamflow data measured and published by the U.S. Geological Survey was used exclusively in all hydrologic analyses performed as part of this study. Of the approximately 15 USGS streamflow (water discharge) stations currently in operation in the State of Rhode Island, the gage on the Wood River at Hope Valley was selected because of its relatively unregulated status and long term (1942 to present) discharge record. Also an upstream gage on this river near Arcadia, RI, was analyzed for its period of record encompassing the 1963 to 1966 drought and unregulated streamflow.

Many of Rhode Island's streams and rivers are regulated by mill ponds and natural streamflow is affected by diversions. The paucity of long term, continuous and unregulated streamflow data and the limited number of USGS gages in Rhode Island constrained the selection of surface water discharge station records. However, any occasional regulation of the Moshassuck and Wood Rivers at Hope Valley was considered minor and to have minimal distortion of natural conditions. The Nipmuc River is unregulated as is the Wood River above Arcadia. Regulation on some of the selected streams was considered minor and to have minimal impact on the statistical analysis. Low flow duration frequency runoff data for four USGS gaging stations used in this study are presented in tables 8 through 11.

b. Annual and Multiyear Low Flow Duration Frequencies. An annual low flow frequency analysis was made of the historical flow data having the longest term, Wood River at Hope Valley. Low flows were determined for durations of 3, 7, 14, 30, 90, 183, and 365 days for each climatological year (1 April to 31 March) using the USGS "WATSTORE" data storage and retrieval system. The annual low flows for each duration were fitted to a Log Pearson Type III distribution. The fitting technique involves transforming annual low flow values to logarithmic values and finding the mean, standard deviation and skew coefficient of the logarithms.

Frequency factors for the Pearson Type III distribution can be found in most hydrology texts. The frequency factor is a function of both recurrence interval and skewness. Skewness is a statistic calculated from the data being analyzed, whereas recurrence intervals range from 1 to 100 years for this study. This exercise was facilitated by use of USGS "WATSTORE" automated data retrieval and statistical programs. Selected data was plotted for comparison using "Beard's " plotting positions. The adopted low flow frequency duration curves and plotted data are shown on plate 4. Tables 8 through 11 present low flow frequencies for durations of 3, 7, 14, 30, 90, 183, and 365 days for all the streams studied in this report. Low flow values in tables 8-11 are in units of cubic feet per second (cfs).

TABLE 8

LOW FLOW FREQUENCIES
WOOD RIVER AT HOPE VALLEY, RHODE ISLAND
(Station 01118000, 1942 - 1986)
(Drainage Area = 72.4 Square Miles)

Nonexceedance Probability	Recurrence Interval	Low Flow Values 3-Day	7-Day	14-Day	30-Day	90-Day	183-Day	365-Day
.01	100.00	14.40	15.76	16.92	16.68	19.22	26.36	75.63
.02	50.00	15.37	16.79	17.87	18.07	21.34	30.15	83.18
.05	20.00	16.97	18.54	19.52	20.44	24.97	36.62	95.36
.10	10.00	18.65	20.32	21.25	22.86	28.72	43.26	107.02
.20	5.00	20.96	22.81	23.77	26.27	34.02	52.52	122.14
.50	2.00	26.54	28.87	30.31	34.61	47.08	74.35	153.83
.80	1.25	34.21	37.29	40.20	46.22	65.23	102.14	188.38
.90	1.11	39.34	42.97	47.37	54.07	77.38	119.20	207.20
.96	1.04	45.91	50.31	57.16	64.18	92.86	139.34	227.56
.98	1.02	50.89	55.89	65.00	71.86	104.49	153.42	240.78
.99	1.01	55.94	61.58	73.32	79.67	116.21	166.80	252.64

TABLE 9

LOW FLOW FREQUENCIES
WOOD RIVER NEAR ARCADIA, RHODE ISLAND
(Station 01117800, 1965 - 1986)

Nonexceedance Probability	Recurrence Interval	Low Flow Values 3-Day	7-Day	14-Day	30-Day	90-Day	183-Day	365-Day
.01	100.00	4.07	4.39	4.85	5.25	7.77	10.27	29.07
.02	50.00	4.61	4.95	5.47	6.02	8.76	12.19	33.50
.05	20.00	5.52	5.91	6.52	7.35	10.50	15.57	40.86
.10	10.00	6.45	6.89	7.61	8.73	12.34	19.12	48.08
.20	5.00	7.75	8.29	9.12	10.68	15.01	24.15	57.55
.50	2.00	10.81	11.65	12.74	15.38	21.87	36.14	77.27
.80	1.25	14.78	16.17	17.50	21.57	31.93	51.16	97.59
.90	1.11	17.26	19.09	20.52	25.47	38.94	60.07	107.83
.96	1.04	20.24	22.70	24.20	30.19	48.17	70.23	118.09
.98	1.02	22.35	25.33	26.85	33.54	55.28	77.06	124.23
.99	1.01	24.39	27.91	29.43	36.78	62.58	83.34	129.39

TABLE 10

LOW FLOW FREQUENCIES
MOSHASSUCK RIVER AT PROVIDENCE, RHODE ISLAND
(Station 01114000, 1965 - 1986)

Nonexceedance Probability	Recurrence Interval	Low Flow Values						
		3-Day	7-Day	14-Day	30-Day	90-Day	183-Day	365-Day
.01	100.00	1.36	2.02	2.65	4.95	6.31	8.76	18.94
.02	50.00	1.74	2.44	3.09	5.34	6.85	9.61	20.75
.05	20.00	2.46	3.17	3.84	6.00	7.80	11.08	23.72
.10	10.00	3.22	3.93	4.60	6.68	8.80	12.59	26.66
.20	5.00	4.30	4.99	5.65	7.62	10.28	14.73	30.61
.50	2.00	6.67	7.39	8.00	9.92	14.16	20.06	39.48
.80	1.25	9.03	10.09	10.73	13.09	20.15	27.60	50.30
.90	1.11	10.10	11.53	12.24	15.22	24.57	32.75	56.82
.96	1.04	11.05	13.03	13.89	17.95	30.66	39.42	64.47
.98	1.02	11.55	13.95	14.95	20.01	35.59	44.52	69.81
.99	1.01	11.91	14.74	15.90	22.10	40.86	49.737	74.89

TABLE 11

LOW FLOW FREQUENCIES
NIPMUC RIVER NEAR HARRISVILLE, RHODE ISLAND
(Station 01111300, 1965 - 1986)

Nonexceedance Probability	Recurrence Interval	Low Flow Values 3-Day	7-Day	14-Day	30-Day	90-Day	183-Day	365-Day
.01	100.00	0.10	0.14	0.23	0.29	0.46	1.24	10.19
.02	50.00	0.14	0.18	0.28	0.35	0.59	1.70	11.89
.05	20.00	0.20	0.25	0.36	0.46	0.84	2.61	14.78
.10	10.00	0.29	0.34	0.45	0.58	1.15	3.70	17.66
.20	5.00	0.43	0.48	0.61	0.79	1.67	5.40	21.54
.50	2.00	0.86	0.93	1.09	1.49	3.27	9.75	29.86
.80	1.25	1.62	1.75	2.03	2.92	6.19	15.09	38.80
.90	1.11	2.19	2.42	2.84	4.25	8.49	17.93	43.45
.96	1.04	2.96	3.40	4.11	6.42	11.78	20.78	48.22
.98	1.02	3.55	4.22	5.25	8.46	14.46	22.44	51.14
.99	1.01	4.16	5.12	6.57	10.90	17.31	23.79	53.63

Low flow frequency-duration curves were also determined for periods exceeding 1 year. Multiyear low flow analyses are critical in establishing dependable yield of water supply systems with appreciable "carry-over" storage. Analyses were made using a procedure similar to that described in the Journal of Geophysical Research, Vol. 66, No. 12, December 1961, "A Partial Duration Series for Low Flow Analyses," by John B. Stall and James C. Neil. The method is also similar to that described in the "Handbook of Applied Hydrology," 1964 edition, by V.T. Chow, pages 18-11 to 18-15. The study was facilitated by use of the Corps of Engineers Hydrologic Engineering Center Computer Program 723-G1-L2290 entitled, "Partial Duration -Independent Low Flow Events." The procedure is basically as follows: (1) a running total of monthly flows for a selected duration is determined for the entire period of record, (2) the running total is then scanned to determine the lowest flow in the period of record, (3) once this value is determined, to avoid overlapping of data, all running total data for one duration prior and subsequent to this total value is removed from further consideration and the list is again scanned for the second lowest independent event in the period of record. The process of data elimination limits the array of low flow events that can be determined. The recurrence interval or plotting positions of the low flow events are computed using "Beard's" plotting formula as presented in "Statistical Methods in Hydrology," Corps of Engineers, Sacramento District, January 1962. Computed low flow frequency curves for durations exceeding one calendar year, using the 45 years of Wood River data, are also illustrated on plate 4.

c. <u>Nonsequential Storage Yield Analyses.</u> The annual and multiyear low flow frequency-duration curves are used to assess the relative severity and indicated return probability of experienced drought events, such as the drought of the sixties, as illustrated by the plotted data on plate 4. Low flow duration statistics are also used to estimate reservoir storage-yields for differing degrees of dependability. Minimum volume runoff of a selected dependability is determined from the low flow frequency-duration curves and plotted versus duration. A 99 percent dependable analysis is shown on plates 5 and 6. The storage requirement for a selected yield and percent dependability is determined by drawing a straight line, with slope equal to the desired yield, tangent to the volume-duration curve of selected dependability. The negative vertical intercept of this line with the "y" axis represents the usable reservoir storage requirement.

Using the above procedure, with the Wood River low flow-duration data, 99 percent dependable yields were determined for a range of storage and the data is plotted on plate 8. Nonsequential analyses permit a probability analysis based on the statistics of all historic flow data without regard to sequence. Such procedures, though highly useful, must be used with caution and generally verified by concurrent sequential analysis of selected historic events. One potential error in the use of nonsequential analyses for determining storage-yield relations is the fact that the analysis assumes the reservoir filled prior to the critical low flow duration being examined and that it will be capable of refilling before the occurrence of another low flow event. The reasonableness of such assumptions, for the range of storages and yields being considered, needs to be tested by sequential analysis.

Nonsequential storage-yield analysis does not take into account seasonal variations in streamflows and the tangent lines do not reflect seasonal variations in demand, whereas, the sequential storage-yield analysis used in the following subparagraph is a hydrologic synthesis technique which assumes that historical records will repeat themselves exactly.

d. Sequential Storage-Yield Analyses. Reservoir-yield analyses by sequential routing is simply the process of adding inflows to a balance of storage and subtracting outflows during a specified critical hydrologic period. One of the most basic graphical methods of sequential analysis is the "mass curve" or "Rippl" method. A mass curve is a plot of accumulated streamflow versus time. The slope of a line on such a graph represents flow rate, and the vertical deviation between the line and the mass curve represents required storage to meet the specified flow rate. Such analyses define the critical drought period and facilitate the development of a relationship between storage and yield at a single project site. Mass curve analyses for the critical 1960's drought are graphically illustrated on plate 7. A mass curve analysis, if sufficient in length, will demonstrate the project's capability and timing of storage refill following maximum drawdown.

Mass curves for the 1960's drought, shown on plate 7 were used to develop storage-yield relations for the three streams having short periods of records and the long term Wood River. The precipitation frequency analysis of the Providence data in paragraph 5g of this report established that the 1960's drought represented about a 1 to 2 percent chance event. The resulting storage-yield data for all 4 streams are comparatively plotted on plate 8. The finally adopted reservoir storage-yield guide curves, based on all analyses, are also shown on plate 8.

e. Low Flow Augmentation and Evaporation Adjustments. For a proposed water supply impoundment, evaporation losses and minimum release (outflow) rates need to be considered. Based on the U.S. Geological Survey Hydrologic Investigations Atlas HA-7, the average annual loss by evaporation from lakes in Rhode Island is about 26 inches; whereas, loss by evapotranspiration from land area is about 20 inches. This results in an average net loss of 6 inches from land area replaced with lakes, excluding seepage losses from the reservoir area.

In most cases reservoir areas represent such a small percentage of the total watershed area that any adjustments in yield due to increased lake evaporation over land area are quite negligible. However, in those instances where reservoir area represents much of the watershed area, an adjustment may be appropriate. An average annual net loss of 6 inches per year, assuming 75 percent of it occurred during the 6-month summer season, May to October, would result in an average loss in yield during the 6-month period of approximately 0.001 cfs (646 gallons/day) per acre of reservoir area.

Typically, a value of 0.2 cfs per square mile of drainage area is used for the minimum instantaneous release rate to satisfy downstream requirements; however, this requirement might be lessened in times of severe drought.

f. Scituate Reservoir. The State's major public water supply is the Scituate Reservoir, which has a drainage area of 92.8 square miles and a total usable storage capacity of 122,000 acre-feet (24.7 inches of runoff). This impoundment serves the metropolitan Providence area, approximately 80 percent of the State's population. In past Corps of Engineers studies (references c and d), it has been reported that Scituate Reservoir has a maximum dependable yield of 137 cfs (89 mgd). The minimum flow requirement downstream of the reservoir is approximately 18 cfs (11.6 mgd) which reduces the dependable yield to about 119 cfs (77 mgd). This yield is based on utilizing 100 percent of available storage during the 1960's drought conditions. It was also reported (reference d) that the Scituate system could supply a continuous yield, after downstream releases, of 68 mgd without exhausting more than 80 percent of storage during the 1960's drought.

Present operation of the Scituate Reservoir is governed, in part, by a 1915 Act, which stipulates that water withdrawal at Scituate cannot be less than 108 cfs (70 mgd) and what is not needed for domestic water supply must be discharged downstream to the North Branch Pawtuxet River. There is a provision for the draft to be reduced to 100 cfs (65 mgd) in years when the reservoir fails to refill to spillway crest. The purpose of this stipulation is to ensure that the project storage is operated to provide a reasonable yield and that flow in excess of domestic needs is released for downstream low flow maintenance.

7. SUMMARY

The developed reservoir storage-yield relationships per unit watershed area, shown on plate 8, can be used as guidance for estimating the probable safe yields of surface water systems in Rhode Island and are not a substitute for more in-depth site specific project design studies. The storage-yield curves were based on a review of the hydrology of Rhode Island, its drought history, and a nonsequential statistical analysis of streamflow records as well as sequential analyses of the record 1960's drought at selected small gaged watersheds. Upper and lower limit guide curves are presented on plate 8 because of the variation in yields as determined by analysis of streamflow data from the four sites previously mentioned in this report. The record drought compared hydrologically with a 1 to 2 percent chance statistical drought and was used in developing the adopted storage-yield relationships.

8. LIST OF REFERENCES

a. Water Resource Study - Blackstone River Basin, Massachusetts and Rhode Island Hydrology and Hydraulic Studies, CE Maguire, Inc. 1976, and Appendix 8 - Hydrologic Analysis, Department of the Army, New England Division, Corps of Engineers, Waltham, Massachusetts, 1981.

b. Flood Control Reanalysis, Pawtuxet River Basin, Rhode Island, U.S. Army Corps of Engineers, New England Division, June 1987.

c. Big River Reservoir Project, Interim Report, Volume I - Main Report, July 1981.

d. Hydrologic Analysis for Big River Reservoir Project, Pawtuxet River Basin, U.S. Army Corps of Engineers, New England Division, June 1979.

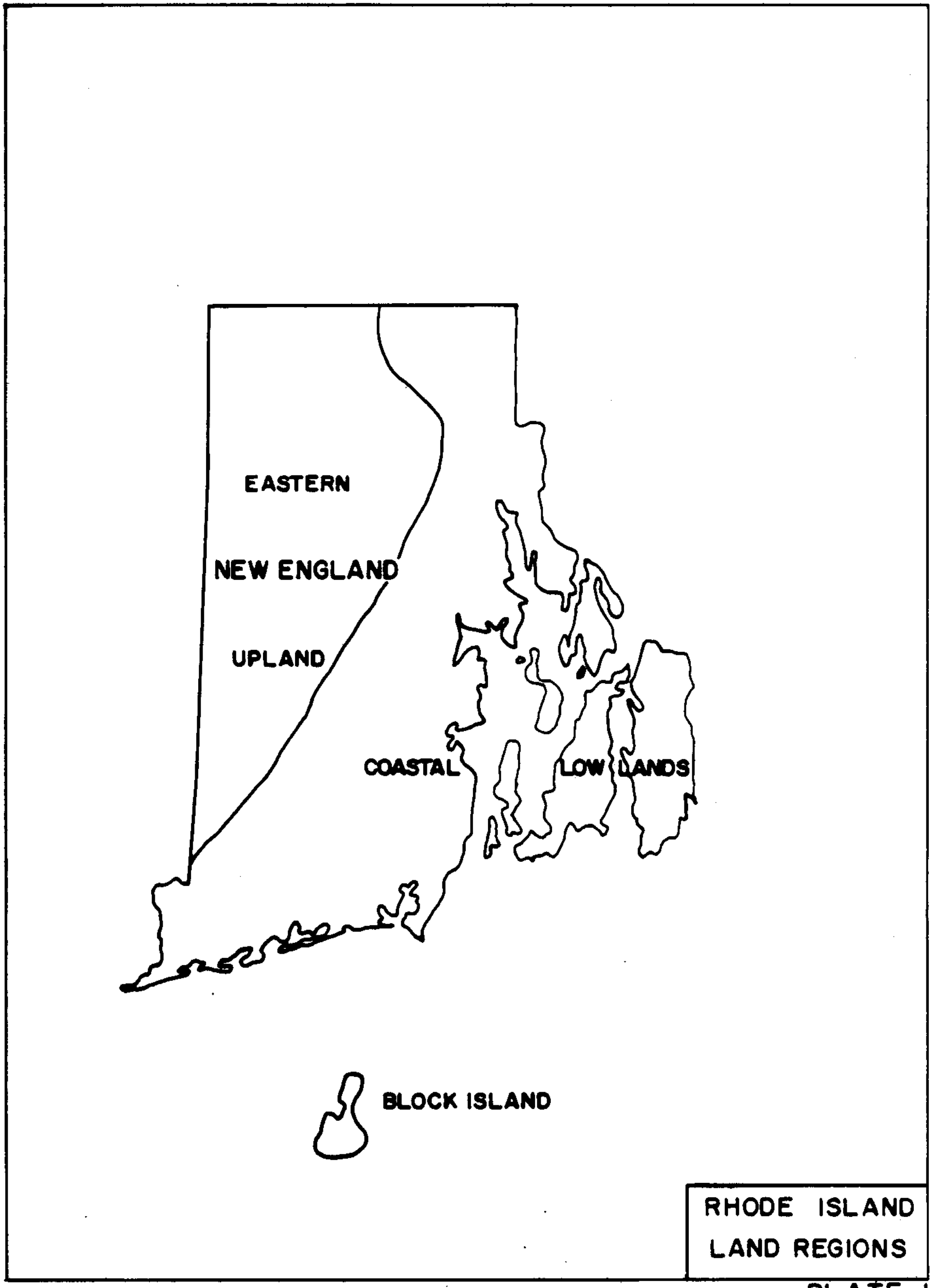
e. Pawtuxet River Basin, Rhode Island, Appendix A - Flood Hydrology Review, U.S. Army Corps of Engineers, New England Division, September 1984.

f. Pawtuxet River Basin, Rhode Island, "Flood Control by Chance or Design," A Hydrologic Analysis of Scituate and Big River Reservoirs, New England Division, Corps of Engineers, December 1986.

g. Detailed Project Report/Environmental Assessment, Blackstone River, Cumberland (Berkeley), Rhode Island - Local Flood Protection, New England Division, Corps of Engineers, 1983.

h. U.S. Geological Survey Water Resources Data Reports - Miscellaneous Volumes.

i. National Oceanic and Atmospheric Administration - Climatological Data, Miscellaneous Volumes.


EASTERN
NEW ENGLAND
UPLAND
COASTAL
LOW LANDS
BLOCK ISLAND
RHODE ISLAND
LAND REGIONS
PLATE I

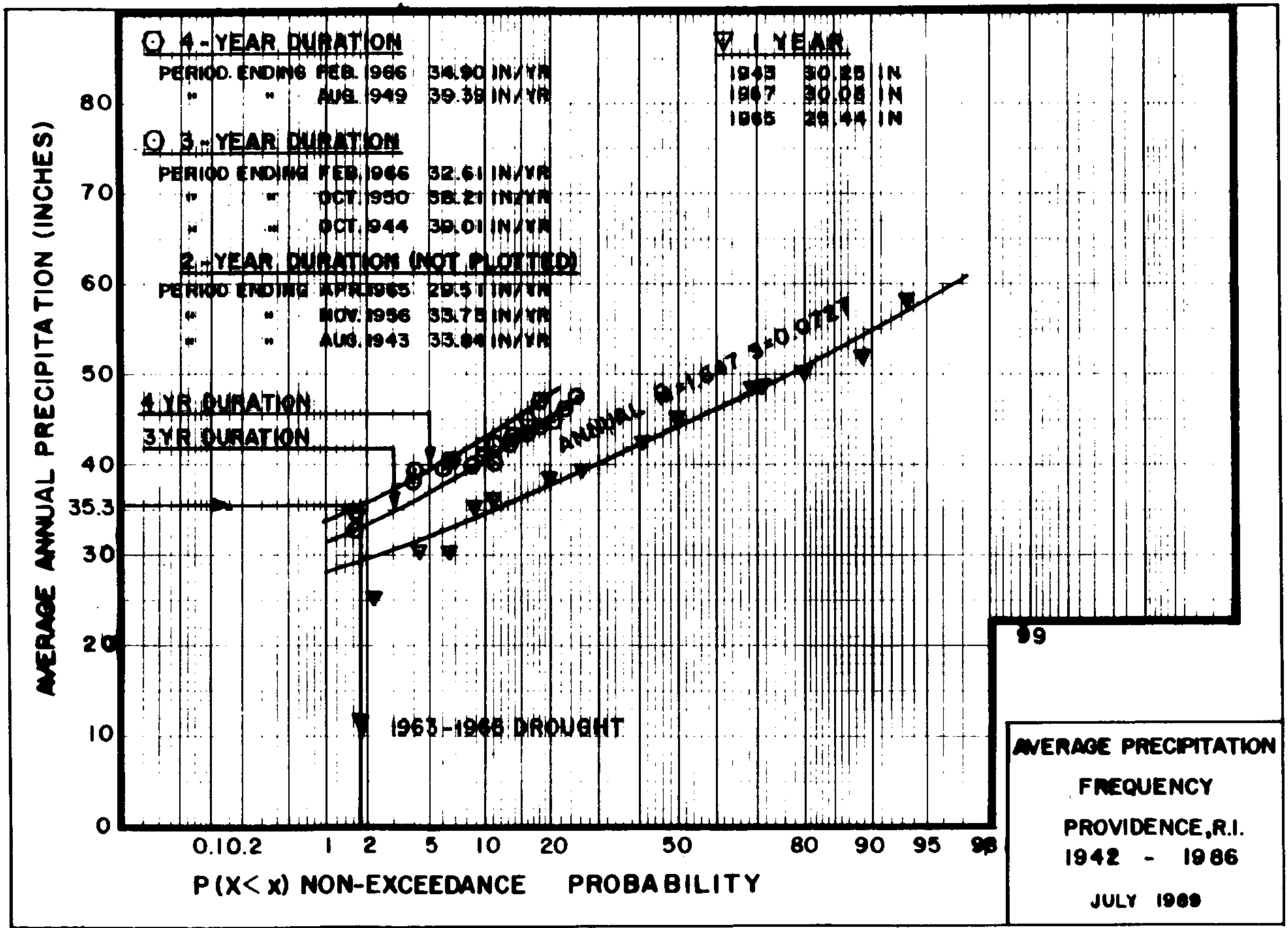

4-YEAR DURATION
PERIOD ENDING FEB. 1966 34.90 IN/YR
" " AUG. 1949 39.39 IN/YR
3-YEAR DURATION
PERIOD ENDING FEB. 1966 32.61 IN/YR
" " OCT. 1950 38.21 IN/YR
" " OCT. 1944 39.01 IN/YR
2-YEAR DURATION (NOT PLOTTED)
PERIOD ENDING APR. 1965 29.51 IN/YR
" " NOV. 1956 35.75 IN/YR
" " AUG. 1943 33.84 IN/YR
1 YEAR
1943 30.25 IN
1957 30.05 IN
1965 28.44 IN
4 YR DURATION
3YR DURATION
ANNUAL
1963-1966 DROUGHT
AVERAGE ANNUAL PRECIPITATION (INCHES)
80
70
60
50
40
35.3
30
20
10
0
0.1 0.2
1
2
5
10
20
50
80
90
95
98
99
P(X< x) NON-EXCEEDANCE PROBABILITY
AVERAGE PRECIPITATION FREQUENCY
PROVIDENCE, R.I.
1942 - 1986
JULY 1989

PLATE 2

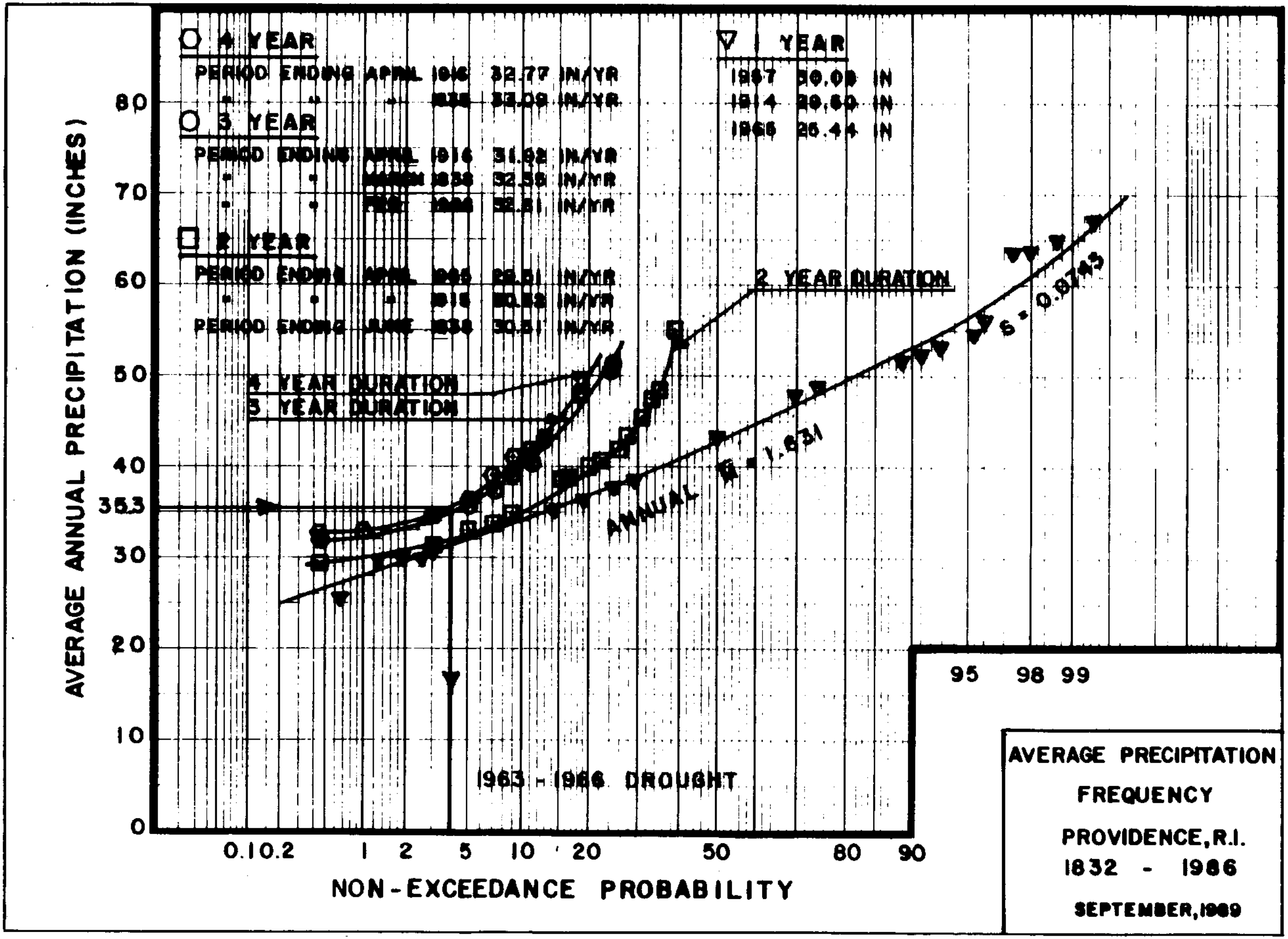
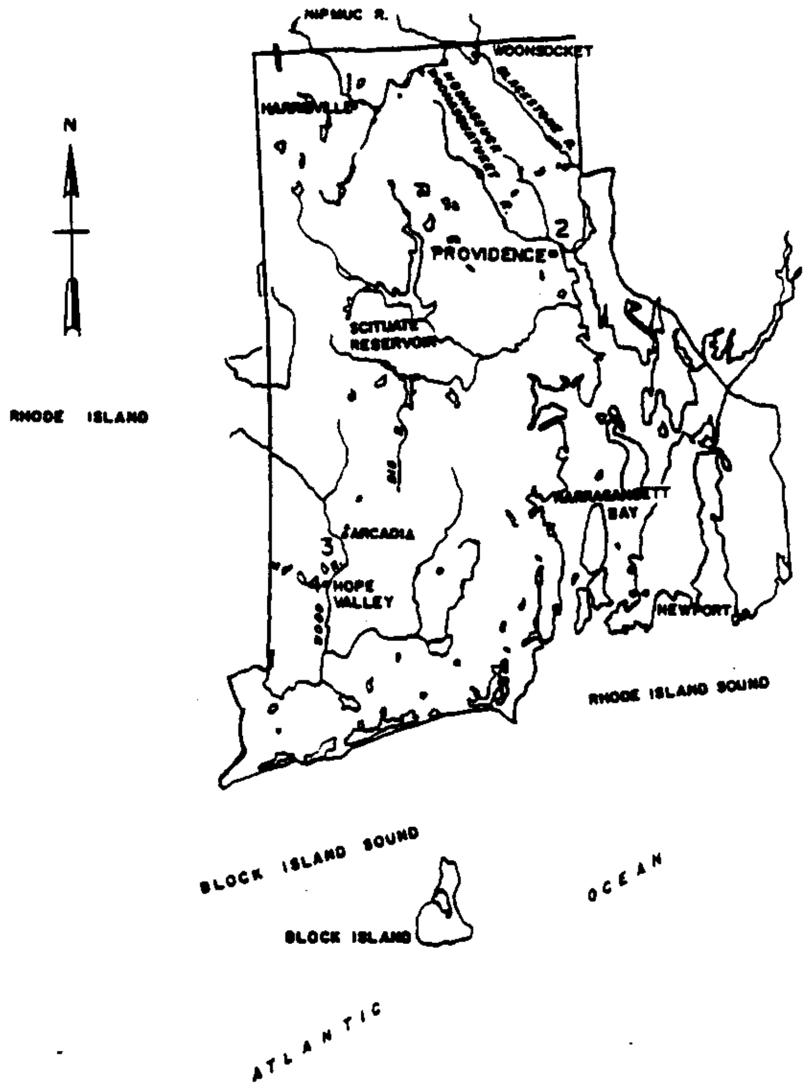

AVERAGE ANNUAL PRECIPITATION (INCHES)
NON-EXCEEDANCE PROBABILITY
4 YEAR DURATION
3 YEAR DURATION
2 YEAR DURATION
ANNUAL
1963 - 1966 DROUGHT
35.3
AVERAGE PRECIPITATION
FREQUENCY
PROVIDENCE, R.I.
1832 - 1986
SEPTEMBER, 1989

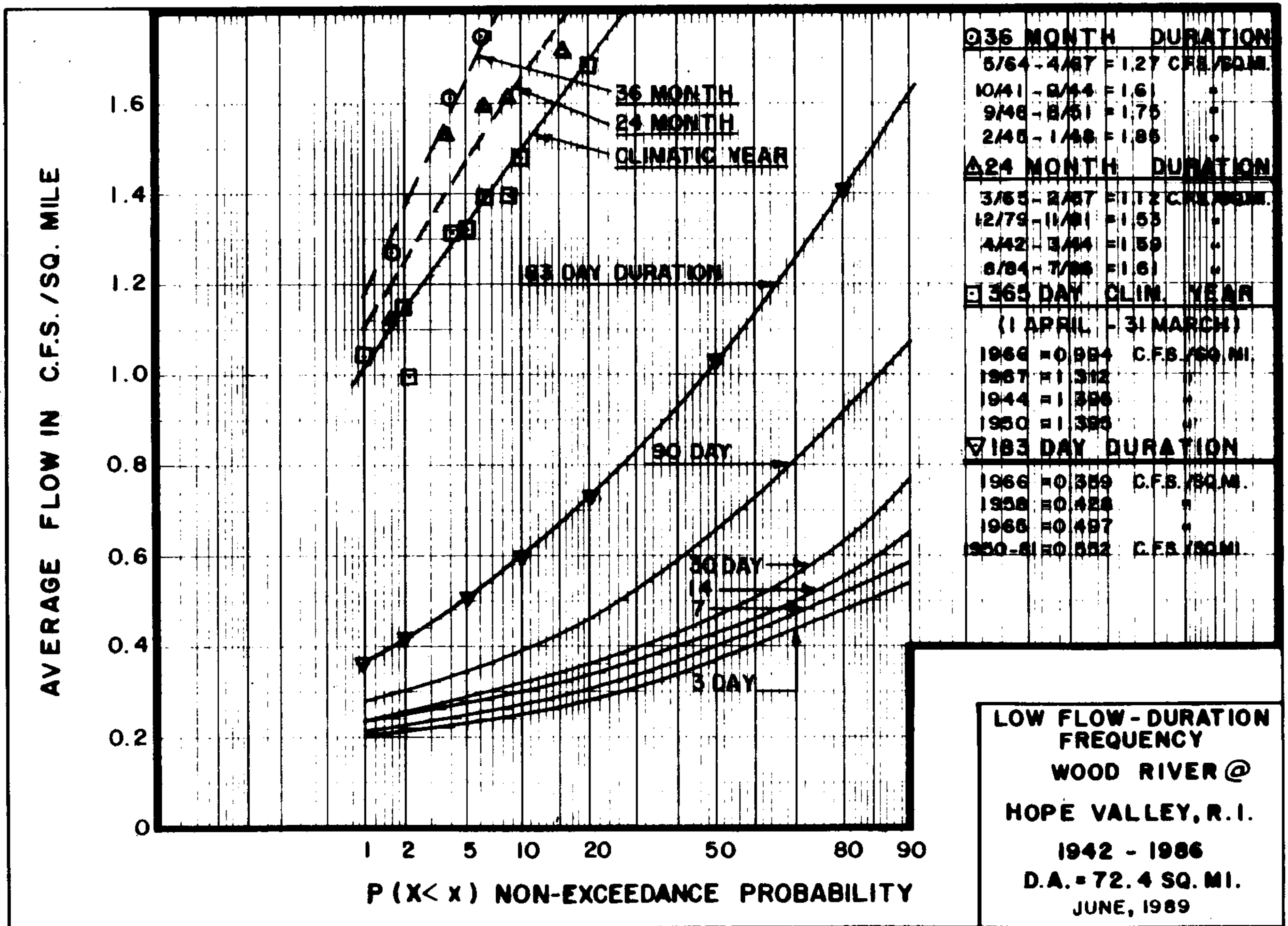
PLATE 2A



1. NIPMUC RIVER NR. HARRISVILLE
2. MOSHASSUCK RIVER AT PROVIDENCE
3. WOOD RIVER NR. ARCADIA
4. WOOD RIVER AT HOPE VALLEY

WATER SUPPLY STUDY
RHODE ISLAND

GAUGE SITES
PLATE 3



LOW FLOW-DURATION FREQUENCY

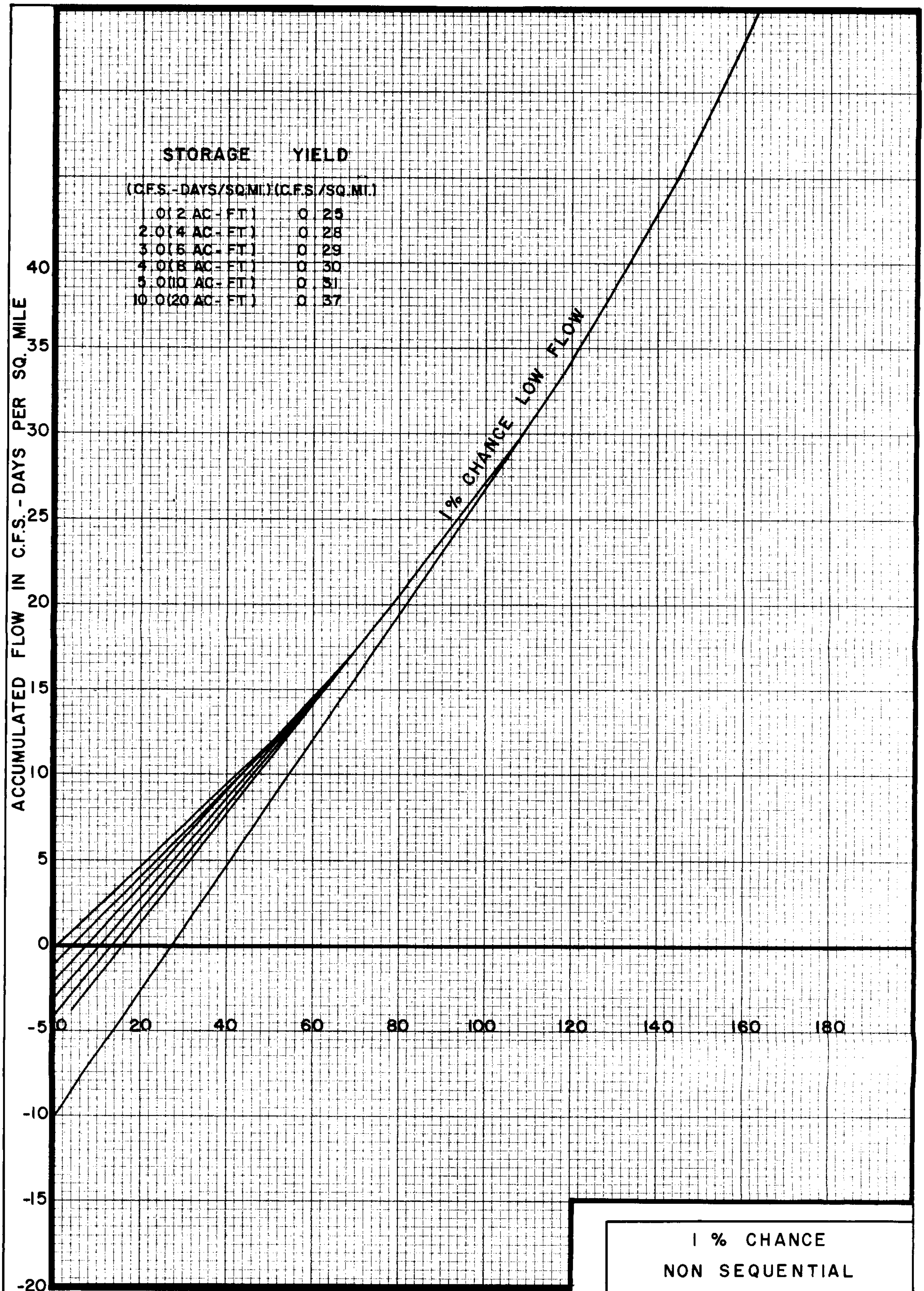
WOOD RIVER @ HOPE VALLEY, R.I.

1942 - 1986

D.A. = 72.4 SQ. MI.

JUNE, 1989

PLATE 4



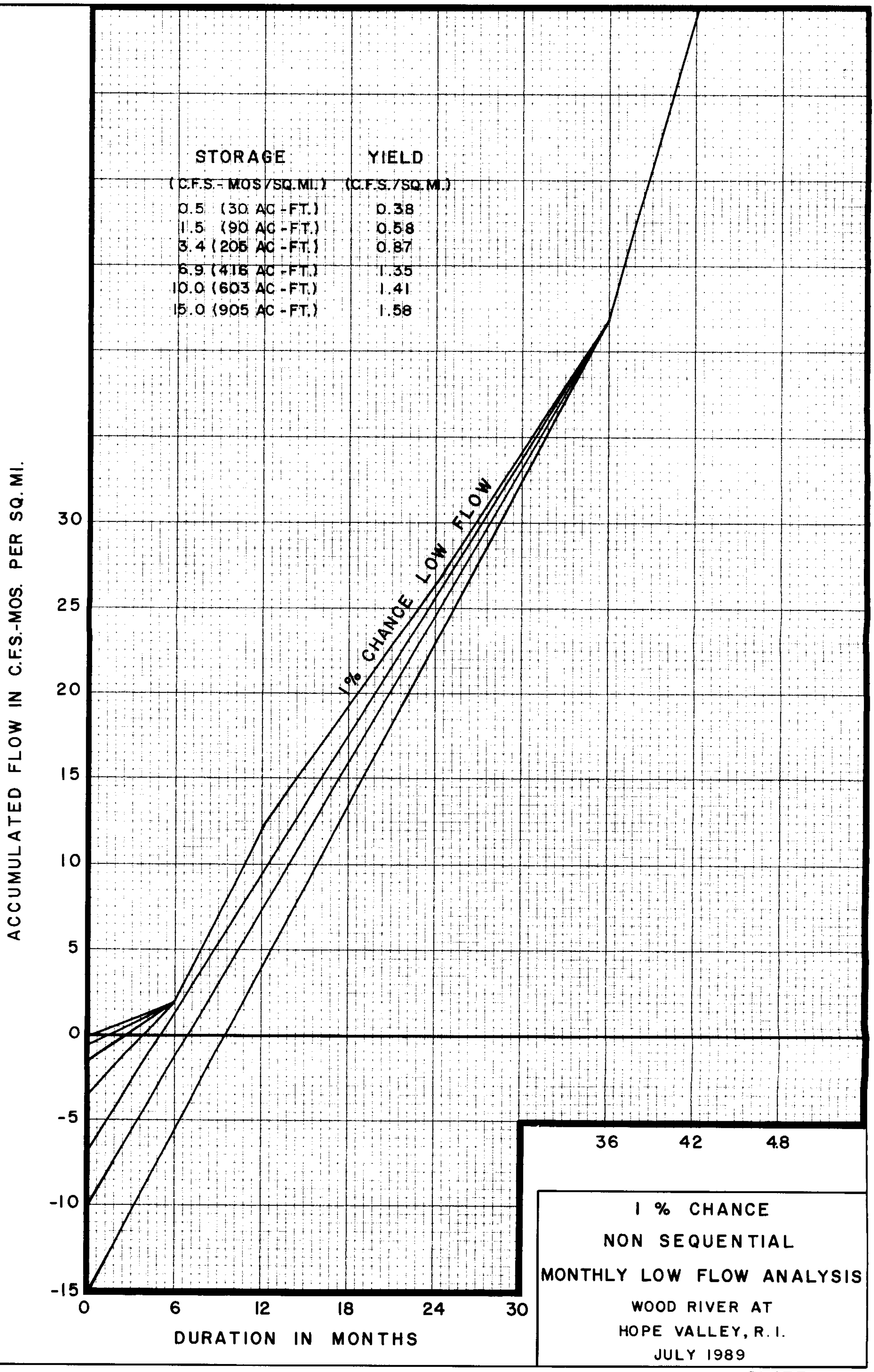
1 % CHANCE

NON SEQUENTIAL

DAILY LOW FLOW ANALYSIS
WOOD RIVER AT
HOPE VALLEY, R.I.

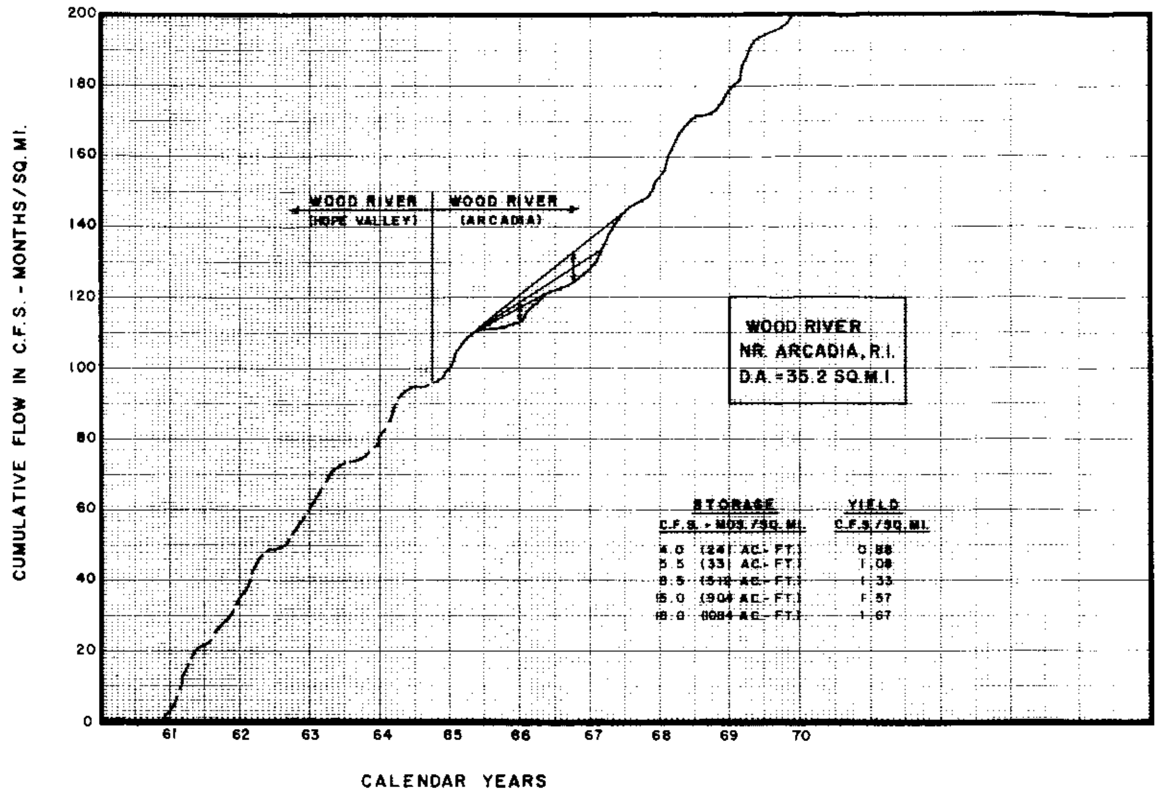
JULY 1989

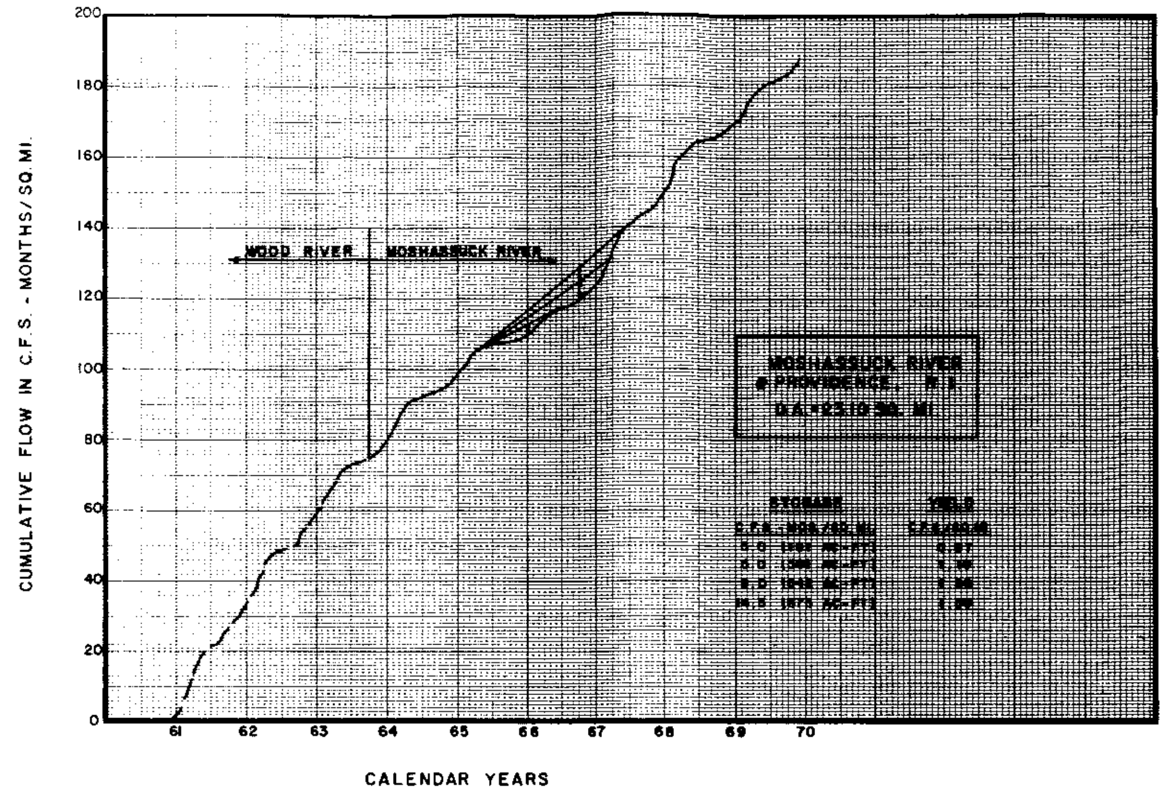
PLATE 5

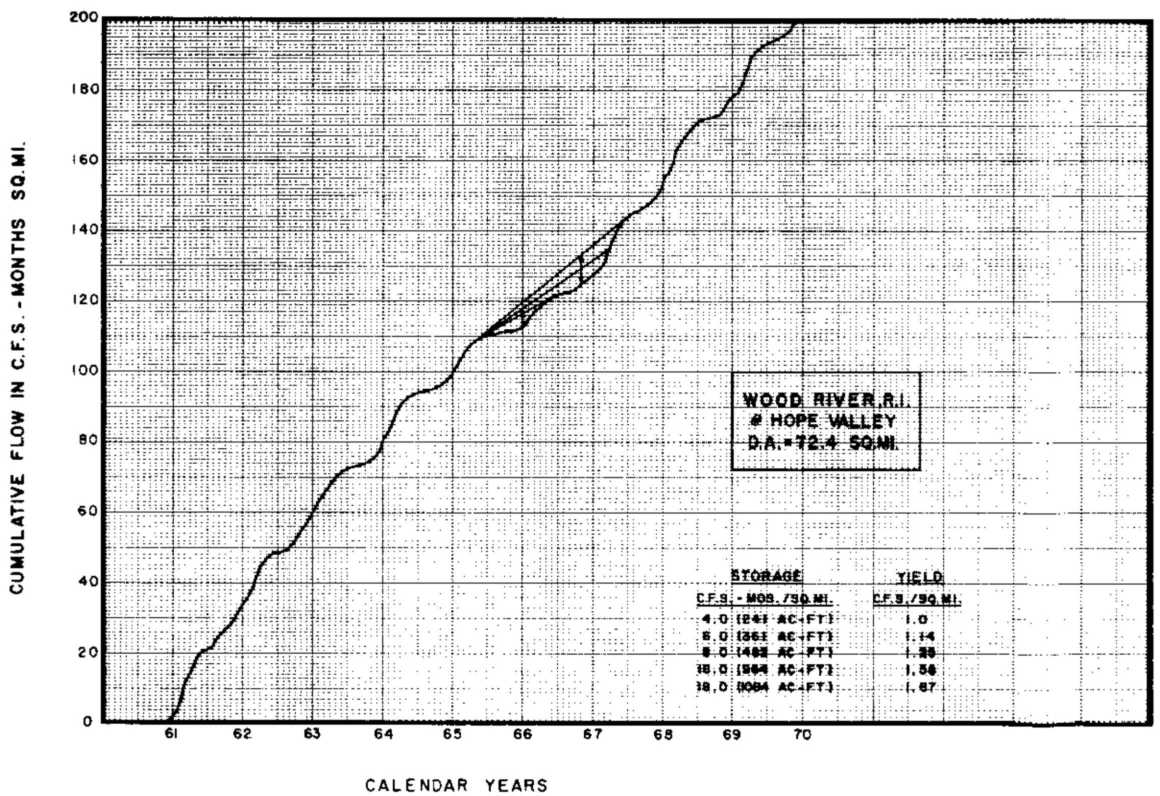


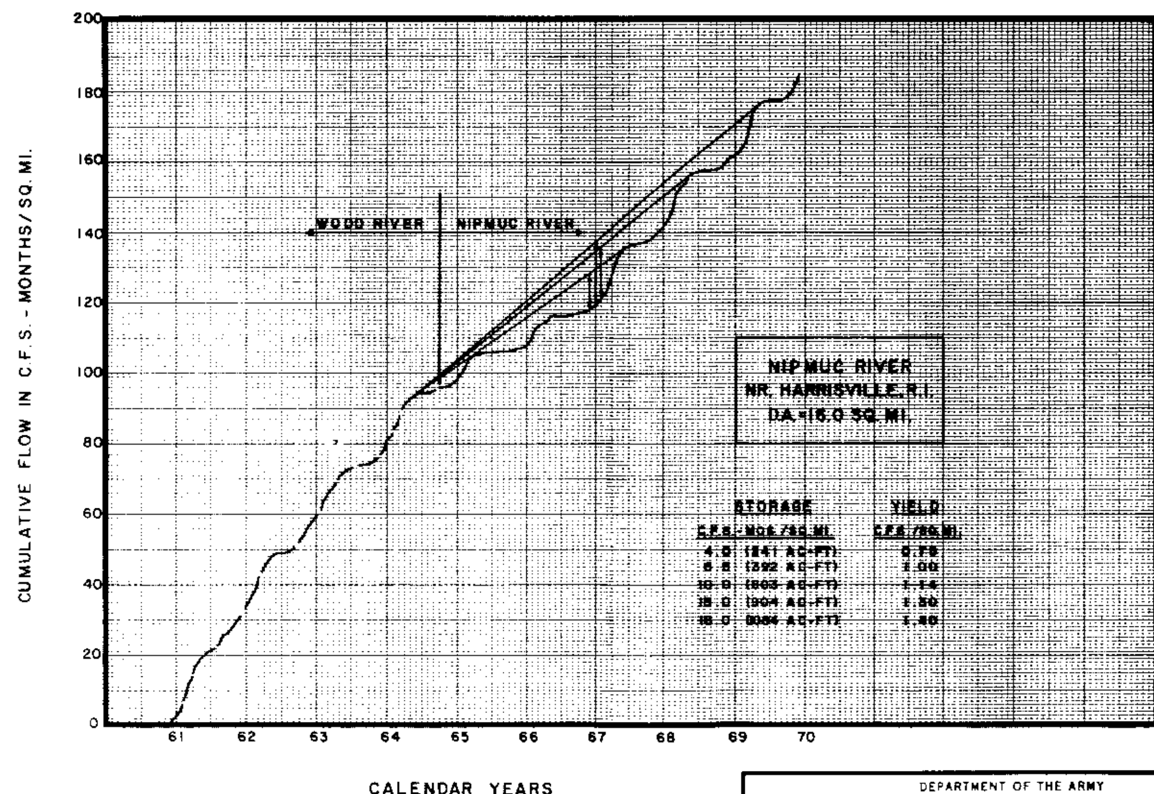
1 % CHANCE
NON SEQUENTIAL
MONTHLY LOW FLOW ANALYSIS
WOOD RIVER AT
HOPE VALLEY, R.I.
JULY 1989

PLATE 6









DEPARTMENT OF THE ARMY
NEW ENGLAND DIVISION
CORPS OF ENGINEERS
WALTHAM, MASS.

SEQUENTIAL

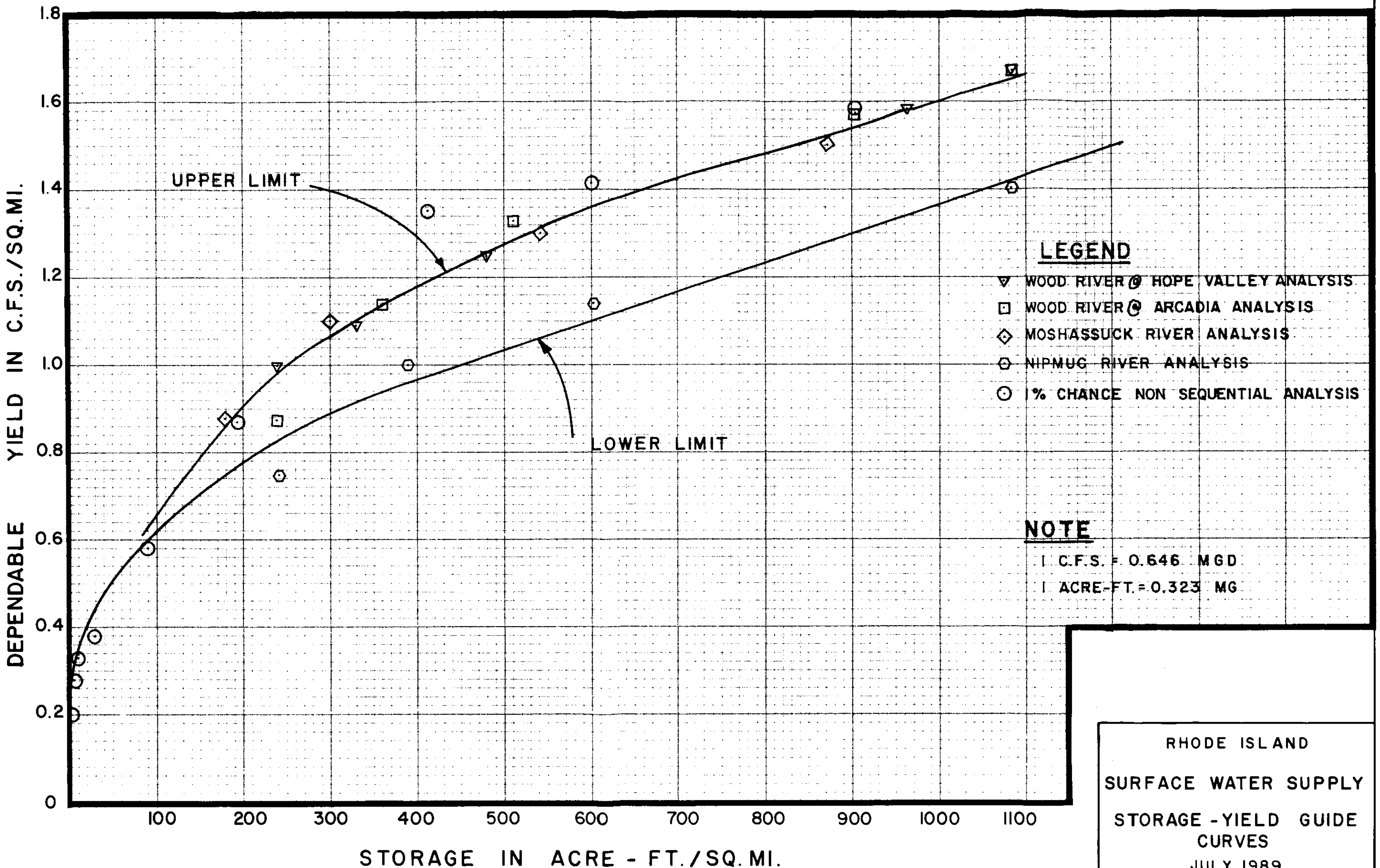
MONTHLY LOW FLOW ANALYSIS

NINETEEN SIXTIES DROUGHT

RHODE ISLAND

HYDRO. ENG. JUNE 1989

PLATE 7



RHODE ISLAND

SURFACE WATER SUPPLY

STORAGE - YIELD GUIDE CURVES

JULY 1989

PLATE 8